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MAPPING THE FUNCTIONAL PROXIMITY OF CORTICAL REGIONS BY MULTIDIMENSIONAL SCALING

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ABSTRACT

Multidimensional scaling procedures provide a new means of studying spatial organization of brain electrical activity. A three-staged analysis process is proposed and tested on human electroencephalographic data. Simple, high accuracy solutions with anatomically meaningful dimensions were achieved. The procedure is not limited to the application presented, but is of general utility.

INTRODUCTION

In the electrophysiological analysis of brain function, elegant and powerful techniques have been developed to study the temporal pattern of activity at a single recording site, but rather less progress has been made in solving the more difficult problems of analyzing the spatial patterning of activity at a number of simultaneously recorded sites (1). Ultimately much of our understanding of the organization of brain functions must depend upon such configurational analyses (2). In the present paper, I report that recently developed techniques of multidimensional scaling provide useful analytic tools for the extraction of information about the functional relations between the sources of simultaneously recorded multichannel electrophysiological data, using the multichannel electroencephalogram (EEG) as an example.

The procedure involved consists of three logically distinct steps. In the first, multi-channel electrophysiological data is acquired from the preparation, inspected for artifacts, preprocessed if necessary, and then stored for analysis. In the second step, some aspect of that data is selected by appropriate feature-selection and proximity estimation algorithms which are applied to all channels of data in a pairwise fashion. The product of this step is a numerical estimate of the similarity or dissimilarity of each pair of channels with respect to the features of interest. In the third step, the resulting proximity matrix is analyzed by a multidimensional scaling procedure to determine both the number of dimensions necessary to reproduce the measured similarity and the configuration of the channels in that multidimensional space.

Nonmetric multidimensional scaling analysis attempts to derive the configuration of points in an N-dimensional Euclidean space such that the distances between points in the configuration are as nearly as possible a monotonic function of the data. As an illustrative example, a proper map of major American cities may be reconstructed from a half matrix of air-

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line distances between these cities when solved in two dimensions (3). In the present investigation, the object is not to reconstruct the spatial configuration of electrodes placed upon the subjects' heads, but to use the scaling method to determine the functional configuration of the brain regions from which the EEG was recorded. Function proximity reflects similarity in electrophysiological activity.

METHOD

EEG was recorded from 10 normal young adults who sat with their eyes closed in a quiet room. Monopolar recordings were taken from both left and right cerebral hemispheres in the frontal (F3 and F4), central (C3 and C4), parietal (P3 and P4) and occipital regions (O1 and O2), with the linked ears as reference. The letter-digit pairs refer to standardized sites for EEG recording, which are illustrated in Figure 1 (4). EEG was amplified by a Beckman R-411 polygraph (bandpass: 0.16-30 Hz, gain: 50 microvolts/cm). Five-sec samples of EEG were digitized at 10 msec intervals and stored on the disc memory of the laboratory computer system (Hewlett-

FIGURE 1

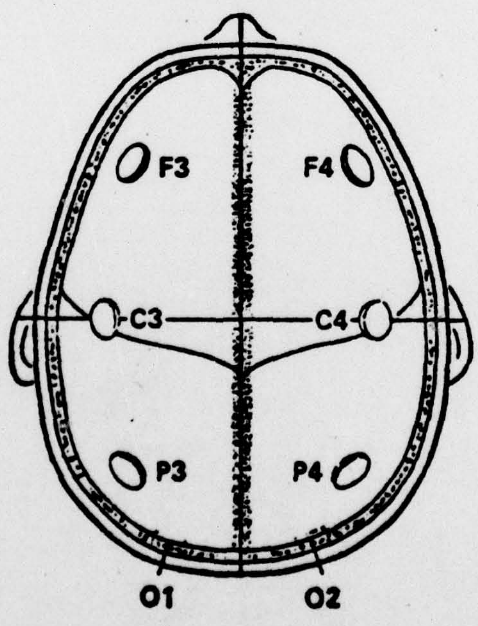

Figure 1. Electroencephalographic recording sites as designated by the conventions of the International 10-20 System (4).

Packard 2116B/2870A). As each 5-sec sample was acquired, the paper record from the polygraph was examined for eye-movement and muscle artifacts. All samples containing visible artifacts were rejected. Twelve artifact-free samples were obtained for each subject. Figure 2 presents a typical 8-channel, 5-sec digitized EEG record.

FIGURE 2

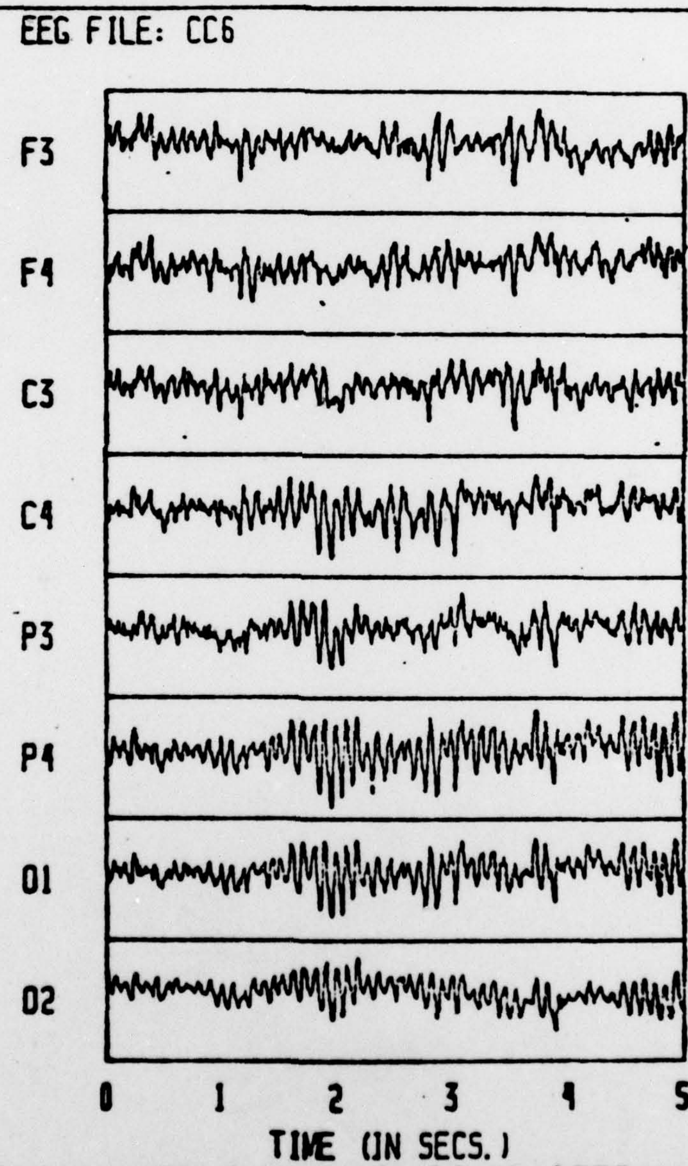

Figure 2. A representative 5-sec sample of digitized EEG recording. Twelve such samples were collected for each of the 10 persons in the experiment.

For each subject, the functional proximity of each pair of EEG channels was estimated with respect to shared synchronous waveforms using the polarity coincidence correlation (PCC) coefficient, which is computed by counting the total number of instances in which the polarities of the two time series are of the same sign, subtracting from that count the number of occasions on which the polarities are of opposite sign, and dividing this difference by the total number of pairs counted. This statistic ranges between +1.0 for perfectly synchronous signals, and -1.0 in the case of perfect phase reversal, with 0.0 indicating a lack of association between the two time series. The PCC coefficient is trigonometrically related to Pearson's product-moment correlation coefficient for Gaussian, ergodic random signals (5), and also, therefore, varies with the value of the conventional cross-correlation function computed at zero time delay.

Since negative values of the PCC seldom are observed in electroencephalographic recording (6), PCC may be considered to reflect the relative amount of synchronous activity between a pair of EEG channels. Two EEG channels that exhibit highly synchronous activity are considered to be functionally close to each other whereas a pair of channels that show little synchrony are considered to be functionally distant.

Harmony and her coworkers (6) have shown that the PCC is a stable parameter of the multichannel electroencephalogram, varying little within a particular individual over repeated tests. Further, the value of the PCC is sensitive to at least some changes in the functional state of the brain; it typically increases during photic driving, for example (6). Moreover, abnormal values of PCC have been reported in children with learning disabilities, suggesting that the measure partially reflects aspects of brain function related to cognitive processing (7). This idea receives some additional support in that Callaway and Harris (8), using a similar measure of cortical coupling, have shown hemisphere-specific changes occurring in verbal and spatial information-processing tasks.

Applying the PCC statistic to all pairs of EEG channels resulted in an 8-by-8 halfmatrix of PCC values for each subject. These proximity matrices then were analyzed for dimensionality and for the configuration of channels within that dimensionality using a general 2-way program for multidimensional scaling, KYST (9). Standard options were employed.

RESULTS

The results of this analysis for each of the 10 subjects appears

in Figure 3. In these solutions, points that cluster together are functionally similar, whereas points separated by greater distances in the solutions are functionally more dissimilar. From these configurations it appears that orderly information concerning functional proximity of brain regions is contained within the multichannel electroencephalogram.

Although the configurational solution may be freely rotated in 2-way Euclidean scaling procedures such as KYST, in the present example the rotation to principal components achieved automatically by the program was sufficient. The two dimensions that appeared are anatomically meaningful and may be labelled anterior-posterior and left-right respectively. On these dimensions, with the exception of a reversal in the occipital channels of Subject 6, every channel is appropriately placed with respect to the other channels given the anatomical arrangements from which the electroencephalogram was recorded (10). But the distances in these configurations do not represent anatomical distances which may be measured in millimeters, but rather reflect functional distances, which are measured in the units required by the algorithm generating the original proximity matrices. In this case the unit of distance reflects the degree of synchronous EEG activity at the various sites measured.

These 2-dimensional configurations represent quite accurate fits to the data. In the KYST procedure for multidimensional scaling, the configurations are altered to minimize "stress", a measure of the badness of the fit. Stress as used here is defined as the ratio of the root mean squared error in estimating the original proximity data from the computed dimensional configuration of distances and the root mean square of the distances in the configuration. Kruskal (11) regards a final stress value of .05 as representing a "good" and .025 as an "excellent" fit to the data by the computed configuration in many situations. By this standard, the fit of the configurations shown in Figure 3 is exceptionally accurate, the stress values of these configurations ranged between .004 and .010 for individual subjects.

With respect to the dimensionality of the solution, the 2-dimensional solutions presented appear to be most adequate. The stress values associated with 1-dimensional solutions were about twenty times as great as those for the 2-dimensional solution, ranging between .080 and .156 for individual subjects. With only 8 points in a configuration, a 3-dimensional solution is not warranted (C).

An examination of the plot of computed distances in the configuration against the corresponding proximities in the PCC matrix (Shepard dia-

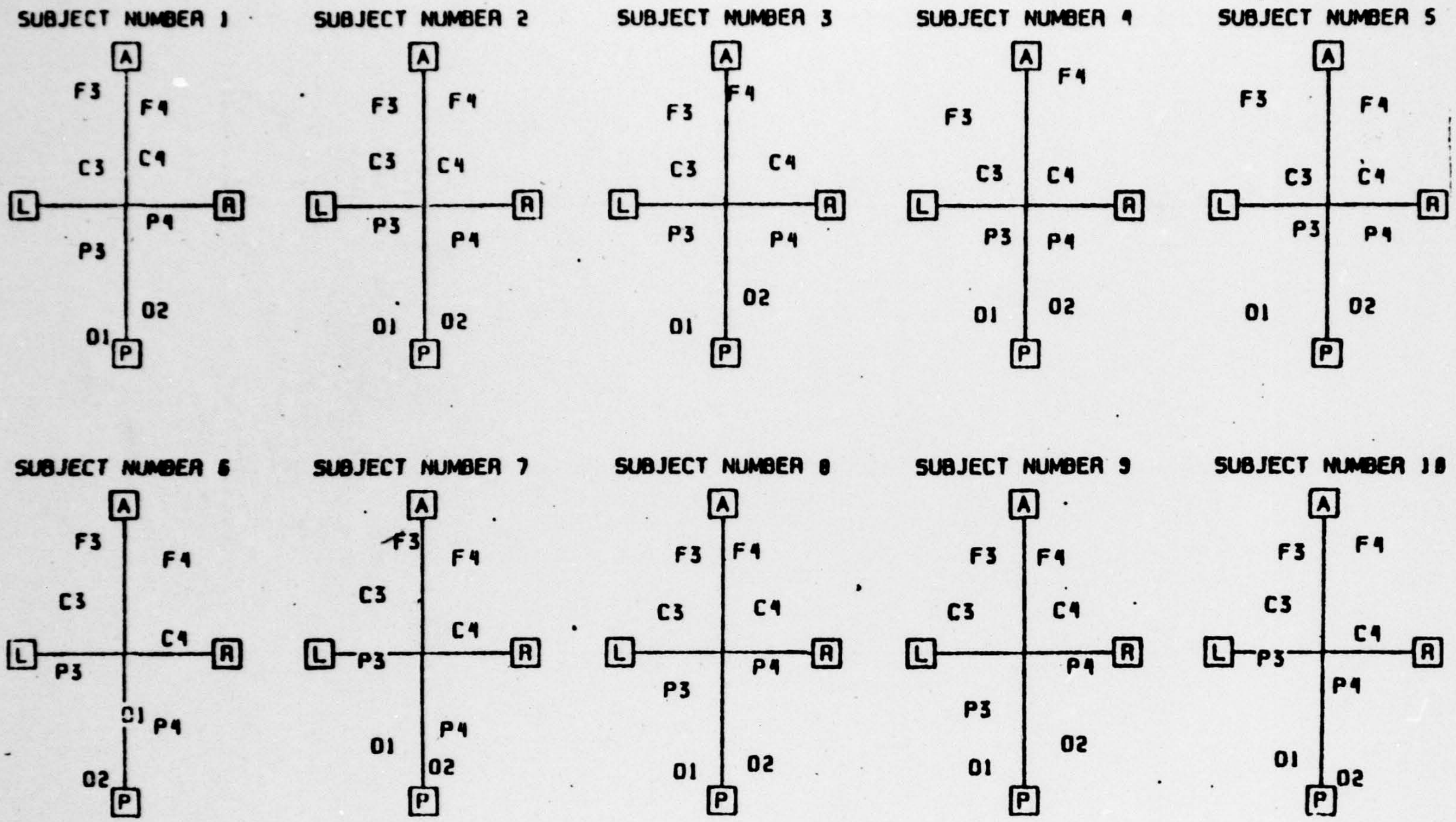

Figure 3. Function configurations of EEG activity at the eight recording sites with respect to shared synchrony as determined by a 2-way multidimensional scaling procedure, KYST. Note the orderly arrangement of points about an anterior-posterior and left-right axis. Functionally more similar points are closer together in this representation. The solutions were reflected on one or both axes for some subjects before plotting to achieve uniformity in the figure.

gram) reveals a linear or near-linear relation for every subject. This indicates that a metric analysis of these data could be employed.

DISCUSSION

The importance of these findings is as follows: First, multidimensional scaling procedures provide a method for clearly visualizing and comprehending the functional organization of electrophysiological activity as it simultaneously appears at a number of recording sites. This provides a solution to one of the most difficult problems in multichannel electrophysiological analysis, representation of the data in a conceptually meaningful form.

Second, this method is not limited to the study of polarity coincidence of the human EEG. Any source of multichannel electrophysiological data may be employed, providing that a substantively meaningful procedure for estimating functional proximity may be found. One obvious application would be in the study of multiple-channel averaged evoked potentials, where a correlation statistic could be used to assess waveform similarity of the potentials and multidimensional scaling to provide a map of functionally related recording sites. Similar approaches could be applied to the study of amplitude variations in extracellular recordings of multiple unit activity in any brain region. Coherence measures of cross-spectral analysis (12) also provide a proximity measure suitable for processing by multidimensional scaling techniques.

Third, differences between configurations may be explored using 3-way multidimensional scaling programs such as INDSCAL (13). This procedure requires linearity in the data. INDSCAL operates on a set of related proximity matrices and extracts a common configuration for the group. Individual configurations are achieved by altering the relative dimension weights of the group solution to fit individual matrices. This procedure is useful both for assessing individual differences, as in evaluating multichannel EEG in normal and neurologically disordered populations, and for studying the effects of various experimental treatments within individuals.

Fourth, the substantive results of the present experiment indicate the presence of a strong pattern of two dimensional spatial organization in human electroencephalogram under resting conditions. The low stress values associated with the solutions obtained for each of the subjects indicates that the configurations obtained in two dimensions fit the actual

data quite closely. The fact that the principal components rotation of the final two dimensional configurations resulted in an anterior-posterior and a left-right axis for each of the 10 subjects suggests that these solutions reflect natural properties of the data.

For these reasons, it appears that multidimensional scaling procedures may provide one solution to the neurophysiological problem of sensibly analyzing and comprehensibly organizing multiple-channel electrophysiological data.

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10. The one exception to perfect anatomical organization in the MDS configuration may be seen in the posterior region for Subject 6. The displacement of the occipital leads O1 and O2 with respect to the remainder of the configuration appears to result from the high functional proximity of sites O1 and P4. This linkage is a stable function of this subject: In each of the 10 5-sec EEG records, the highest PCC value was that between O1 and P4.
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